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VERIFICATION OF THE OPERATIONAL GOES INFRARED RAINFALL ESTIMATION TECHNIQUE OVER THE UPPER MIDWEST

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I.   INTRODUCTION

Since about 1998, the National Weather Service (NWS) has used automated rainfall prediction information from the National Environmental Satellite Data and Information Service (NESDIS) to assist in its local hydrological warning process. This remotely-sensed rainfall prediction information is a Geostationary Operational Environmental Satellite-8 (GOES-8) and -9 infrared (IR), 10.7 um band algorithm developed by Vicente et. .al (1998, hereafter referred to as VIC98) called the auto-estimator. The auto-estimator generates near real-time GOES infrared-based rainfall totals over the contiguous United States (CONUS) for 1-, 3-, 6-, and 24-hour time intervals.

Since the NWS La Crosse forecast area contains about 50% unglaciated terrain, local rapid relief changes on the order of 600-800 feet can cause increased hydrological problems than those typically found in the Midwest. The auto-estimator technique, if properly understood and used operationally by NWS forecasters, can provide another tool to increase the lead time of life and property damaging hydrological events. In that spirit, this work represents a collaborative effort between the NWS, NESDIS, the North-central River Forecast Center (NCRFC), and the University of Wisconsin-La Crosse (UW-L).

For 1998, 24-hour rainfall totals from the auto-estimator are compared and statistically analized with the 24-hour gage rainfall amounts for the same latitude and longitude earth coordinate. Environmental data was also used to segregate possible atmospheric conditions that caused more favorable or less favorable GOES auto-estimator performance. This paper discusses the impact of two atmospheric variables: wind shear and cloud-top temperature.

2.   METHODOLOGY

The main thread of this research was to compare GOES-8 auto-estimator rainfall amounts to the surface rain gage amounts over the same time interval and for the same physical location. In 1998, GOES-8 auto-estimator rainfall estimates were generated at, and supplied by, NESDIS for the research domain (Fig. 1) at 6-h and 24-h time intervals. The 1- and 3-h time intervals, although available from NESDIS, were not investigated in this research due to the limited gage reports over the domain for this time frequency. The auto-estimator uses the GOES-8 infrared (IR) 10.7 um band to compute real-time precipitation amounts based on a power-law regression.
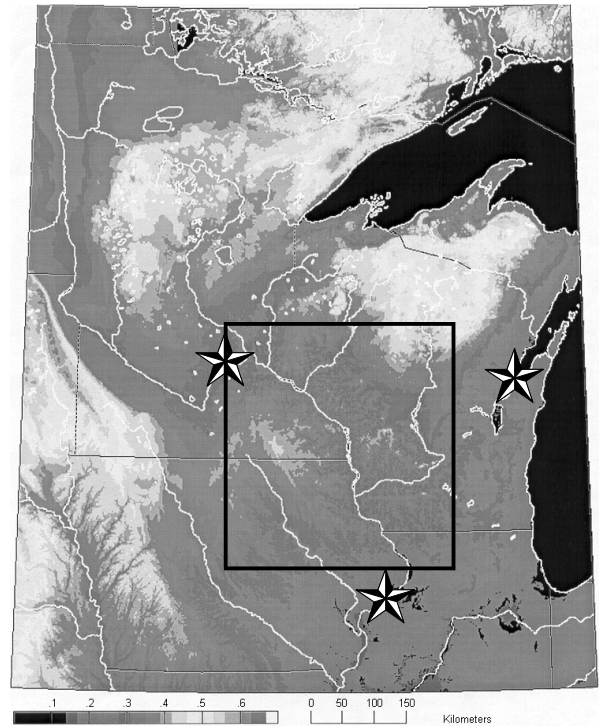

Figure 1. Box indicates the domain for the research area. Map of study area terrain elevation (km) is shown by grey scale. Stars indicate rawinsonde data sites used in study (clockwise, from upper left: KMPX, KGRB, and KDVN).

Due to the nature of satellite remote sensing in the IR band, cloud-top temperature is heavily weighted in the algorithm. The auto-estimator also uses the precipitable water input from the Eta model to enhance the performance. The horizontal resolution of the GOES-8 IR auto-estimator precipitation product is that of the 10.7 um band: 4 km. For more details on the auto-estimator, see VIC98.

Besides a thorough explanation of the GOES auto-estimator provided by VIC98, the authors provide conclusions on its performance. First, the performance was better for short-lived, convective events and poorer for lower-topped (warm) stratiform cloud systems. The auto-estimator was designed for the former. VIC98 found that warm cloud-top rain events typically were underestimated.   These systems generate flooding events due to longer duration rainfall versus high-intensity, short-duration precipitation as in the cold cloud-

top cases. Because of this, they urged caution in the use of the 24-h daily rainfall accumulation product. Second, the GOES auto-estimator overestimates the area of rainfall with slow moving mesoscale convective systems (MCSs) having large cirrus shields. Third, there is a tendency to underestimate (over-) low (high) rainfall rates. It must be pointed out that VIC98 used WSR-88D radar estimates as rainfall verification over a gridded, 12 km horizontal resolution grid versus rainfall gage point data as used in this research.

The NCRFC collected and supplied 24 hour daily rain gage data across the research domain for 1998 which was the basis for the research. These gage data included first and second order (manual and automated) surface rainfall gages as well as "unofficial" Cooperative (UCO-OP) Network gage reports. The UCO-OP network 24-h rain gage reports are telephoned into the local NWS office from volunteers. The authors acknowledge that the rain gage data may have errors. The NCRFC does run limited quality control on these data and the NWS local personnel screen UCO-OP reports.

Over 4000 gage reports (with "zeros" removed) were collected for the study during the months from April to November 1998. Comparisons were made between the GOES 24-h (1200-1200 UTC) satellite auto-estimator output and the 24-h observed precipitation report from the matching gage location (hereafter referred to as one "case"). Although the auto-estimator domain included 14,000 pixels at 4 km horizontal resolution, only those pixels matching the gage reports for a given 24 hour period were used. The observed precipitation amounts (gages) were consolidated into three ranges to make for ease in the GOES auto-estimator comparison analysis: less than 0.25" (LT25), 0.25"<1.00", and greater than 1.00" (GT100). Statistical analysis was done on the LT25 group including both "zeros" and "no zeros". "Zeros" are defined as cases where the gage=GOES=0.0. "No zeros" are defined as the LT25 data group with all gage=GOES=0.0 cases *removed*.

Shear	0-6km Shear (10-3 s^{-1})	Number of cases
Low	Less than 3.00	997
Medium	3.00 to 4.99	2079
High	5.00 and greater	1342

Table 1. Wind shear category values and number of cases for the low, medium, and high wind shear groups.

Environmental data was used in this research to assess the behavior of the algorithm for various kinematic and thermodynamic conditions. Rawinsonde data from three unique sites surrounding the domain was acquired and linearly averaged to represent the entire domain's environmental structure (see Fig. 1). Since the 24-h gage and GOES algorithm sampling interval extended from 1200-1200 UTC, 0000 UTC rawinsonde data was used

Cloud-Top	Mean (KFt)	PMAX Lifted Index	Number of cases
Warm	20	4	2356
Cold	48	-4	2062

Table 2. Cloud-top category mean maximum parcel level (MPL), most unstable parcel lifted index from the lowest 200 mb, and number of cases for the warm and cold cloud-top groups.

from the three sites in order to (1) represent mid-point environmental conditions temporally and (2) capture maximum thermodynamic instability and buoyancy. The authors hoped that by assessing the data set herein using rawinsonde parameters, operational forecasters could achieve a forecasted auto-estimator bias/behavior based on forecasted environmental kinematic and thermodynamic structure.

0-6 km wind shear was used to assess the magnitude of the ambient environmental wind shear. The

Observed Rainfall Amount	Less than 0.25" < Zeros included >	Less than 0.25" < Zeros no included >	0.25" to 0.99"	1.00" and Greater	Total < Zeros not included >
GOES Underestimate					
Mean Error	0.075	0.075	**0.354**	**0.815**	0.343
Standard Deviation	0.066	0.066	**0.224**	**0.501**	0.363
Number of cases	642	642	985	340	1967
GOES Overestimate					
Mean Error	0.420	0.420	**0.900**	**1.402**	-0.621
Standard Deviation	0.511	0.511	**0.963**	**1.320**	0.801
Number of cases	1627	1627	606	197	2430
GOES = Gage					
Mean Error	0.000	0.008	0.014	0.150	0.014
Standard Deviation	0.003	0.019	0.090	0.212	0.084
Number of cases	**1139**	**12**	7	2	21
GOES-Gage All Cases					
Mean Error	**-0.188**	**-0.280**	-0.123	0.002	**-0.189**
Standard Deviation	**0.420**	**0.488**	0.867	1.390	**0.800**
Number of cases	3408	2281	1598	539	4418

Table 3. Comparison of the mean error (in.), standard deviation (in.), and sample size for the three precipitation classes and total. Boldface type shows most significant statistical values.

0-6 km wind shear is defined as the magnitude of the vector difference between the 6km wind and surface wind (divided by 6 km). All cases for a particular 24-h period were grouped into either low, medium or high shear (Table 1). Therefore, the high (low) shear category represents a wind shear vector magnitude of over 30ms^{-1} (less than 18 ms^{-1}) from the surface to 6 km. Environmental cloud-top height estimates were also achieved from the rawinsonde data by calculating the maximum parcel level (MPL). Using the MPL, in conjunction with visual inspection of the soundings, the data were categorized into warm and cold cloud-top categories (Table 2). Generally, the warm-top (cold-top) cloud category contained MPLs of 35 KFT or lower (above 35 KFt).

3. ANALYSIS AND RESULTS

The authors inspected the LT25 precipitation range for both the "zeros" and the "no zeros" group (Table 1). It was found that the "zeros" group (gage=GOES=0.0 included) did have a GOES auto-estimator mean error (ME) of -0.l9" (negative implies the GOES was underestimating). Inclusion of the gage=GOES=0.0 data points reduced the mean error by approximately 0.10", although the standard deviation (STD) was roughly equal at nearly one-half inch.

Increasing observed precipitation amount produced smaller GOES auto-estimator ME (Fig. 2). However, the uncertainty of the GOES algorithm output (STD) grew immensely with increasing precipitation amount. The GOES ME for the GT100 rainfall group was 0.002", which seems remarkably encouraging, however the STD was nearly 1.40". This large STD around a ME of near zero indicates the GOES algorithm is producing random errors and not a consistent bias. This element is troubling for use in operational forecasting. Upon breaking the GOES auto-estimator errors into under- and overestimate groups, more information can be gleaned about the behavior of the output (Table 3). Of the 1591 cases that were either over- or underestimated in the 0.25"<1.00" group, 62% were underestimated. However, it was the GOES overestimates in that group, 48% of the cases, that had a more significant ME of 0.90" and an STD of 0.96". These overestimates grew to a 1.40" ME and a 1.32" STD for the GT100 precipitation group. Overestimates for this group, which most affect life and property, accounted for 37% of the GT100 cases and would tend to lead to false alarms in the NWS warning program. GOES underestimates in this precipitation class were more frequent and yielded a ME of 0.82 - nearly half that of the overestimate group. Therefore the error and uncertainty is much greater for GOES overestimates for precipitation amounts of over 0.25", however this is also less likely to occur.

Segregation of the cases into measured wind shear regimes reveals that as the wind shear increases, the GOES algorithm trends toward overestimation (Fig. 3). This is true for all precipitation categories but becomes more pronounced with increasing precipitation amount. For 24-h rainfall events of GT100, low shear environments produced a GOES *underestimated* ME of 0.71" while high wind shear causes an *overestimate*d ME of more than 0.50" . The STD (not shown) for the low and high wind shear environments was remarkable: 0.59" increasing to
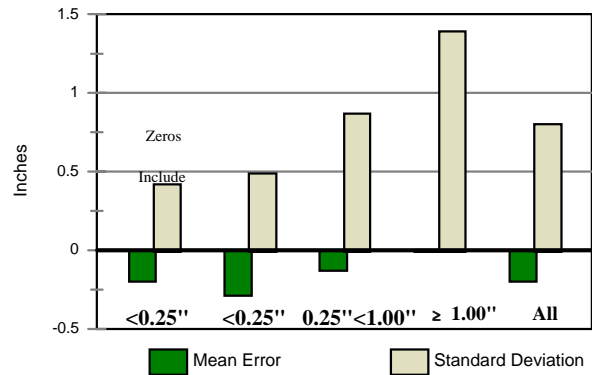

Figure 2. Mean error (dark, in.) and standard deviation (light, in.) for the GOES auto-estimator algorithm for the less than 0.25", 0.25"<1.00", $\geq$1.00", and total observed precipitation ranges. Negative (positive) mean error indicates a GOES auto-estimator overestimate (underestimate).

1.80", respectively. The tendency for the GOES auto-estimator to overestimate for increasing wind shear could be explained in part by the expanse of the anvil cirrus shield away from the true rainfall producing portion of the storm. Since the auto-estimator is weighted heavily toward cloud-top temperature, cold anvil cirrus sampling is likely "fooling" the algorithm over areas which are rain-free below the high-level ice cloud. Although not shown, the GOES ME for the GT100 group in high shear environments was -1.63" (an overestimate) for the cold cloud-top cases versus 0.01" for the warm topped cases. Assuming the cold-top cases represent convective systems, this supports the VIC98 finding that the GOES auto-estimator overestimates the area of rainfall associated with slow-moving MCSs with large cirrus shields. One other explanation for the GOES increasing overestimate tendency for higher shear environments is precipitation efficiency. Foote and Frankhauser (1973), Auer and Marwitz (1968), and others have shown that for higher shear environments, precipitation efficiency decreases, mostly due to increased entrainment Foote and Fankhauser found a precipitation efficiency near 15% for the shear category described as "high" in this paper. While the GOES algorithm is knowledgeable about the precipitable water structure of the environment, the efficiency in producing precipitation from the ambient water vapor is lower in high shear cases. Thus, the possible GOES overestimation.
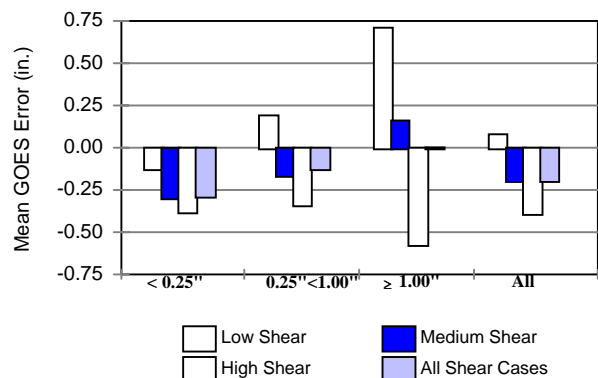

Figure 3. As in Fig. 2, except for low, medium, high, and all 0-6 km wind shear categories described in the text.
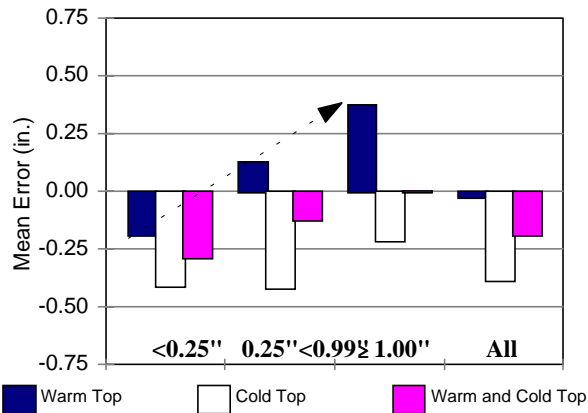
Figure 4. Like Fig.2, except for the warm, cold, and both warm and cold cloud-top categories. Arrow indicates warm cloud-top error trend for increasing rainfall amount.

A clear trend is seen toward GOES underestimating as precipitation amount increases for warmer cloud-top temperatures (Fig. 4). In the GT100 rainfall group, the ME was a GOES underestimate of 0.37" with a STD of 1.03" for warm cloud-top environments. Further, about 75% of the warm cloud-top rainfall reports over 0.25" were underestimated by the GOES auto-estimator algorithm (Fig. 5). Thus, for heavy stratiform rainfall cases, the GOES auto-estimator trends strongly toward underestimating the actual rainfall amount. This is consistent with findings of VIC98. This percentage dropped to near 50% for cold cloud-top environments. When all warm cloud-top cases are valuated the ME is only -0.02". Again, we see more detail on the GOES algorithm behavior when various environmental conditions are segregated in the data. For the cold cloud-top cases in the GT100 group, the ME was a GOES overestimate of 0.21" with a large STD of 1.52". VIC98 designed the GOES auto-estimator for cold cloud-top convective events which may explain the lowest ME being found in this GT100 group (Fig. 4). For every rainfall class, the cold cloud-top environment consistently produced a ME overestimate in the GOES algorithm output.

4.   SUMMARY

Twenty-four hour rain gage reports and GOES auto-estimator output was collected and compared during 1998. The findings generally support those of VIC98 with warm cloud-top cases being underestimated by the GOES auto-estimator. Of the total cases in the GT100 warm cloud-top temperature group, approximately 75% were underestimated. Further, high environmental wind shear caused the GOES auto-estimator to produce mean overestimation errors in all precipitation classes. However, for high shear, cold cloud-top cases in the GT100 group, this overestimate was as large as 1.63".

Overall, the algorithm produced a favorable ME very near zero. It was the STD which was troubling, especially at higher precipitation amounts. For significant flooding rainfall amounts of GT100, the STD was nearly 1.40". This has impact on NWS forecasters using the algorithm output. Although possibly not significant for rainfall amounts over 5-6", it is the 3" rainfall events in short durations that can vary in the algorithm guidance to estimations of roughly 1.50-4.50" based on the STD. This clearly has warning decision implications. It is clear that more work must be done on the short temporal scales of 1- and 3-h GOES auto-estimator verification. Although this research provided more insight into the GOES auto-estimator behavior, more work is needed to ensure its operational usefulness and understanding.

5.   ACKNOWLEDGMENTS

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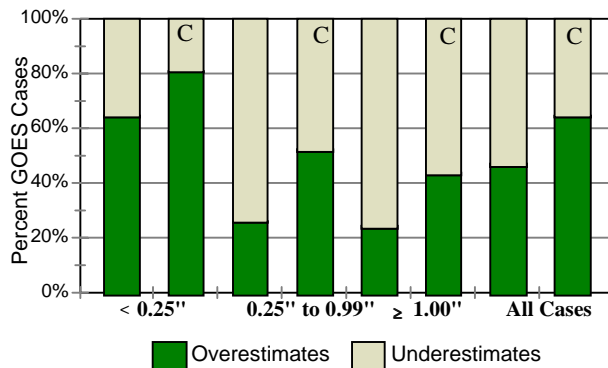

Figure 5. Percent of the total cases where the GOES auto-estimator over- (dark) or underestimated (light) observed gage precipitation for warm and cold (**C**) cloud-top cases. Four observed precipitation ranges are given as in Fig. 2.